Post-Tensioned Concrete Walls and Frames for Seismic-Resistance – A Case Study of the David Brower Center

Mark Stevenson, CE
Leo Panian, SE
Mike Korolyk, CE
David Mar, SE

Tipping Mar + associates
Berkeley, CA

Introduction

This case-study describes an innovative application of post-tensioned concrete construction in the new David Brower Center urban mixed-use development.

Situated in the heart of downtown Berkeley, CA, within 1km of the Hayward Fault, the new complex represents a model of integrated sustainable design. Rated LEED Platinum by the U.S. Green Building Council and named for David Brower, one of the preeminent environmentalists of the 20th century, the center will provide office and meeting space for environmental advocacy and non-profit groups.

To protect the building against the high likelihood of a major earthquake, the structure integrates a unique combination of post-tensioned concrete walls and frames that improve performance, limit damage, and make more efficient use of construction materials.

The defining feature of this system is its unique self-centering behavior, which virtually eliminates permanent post-earthquake deformations. The hybrid system combines the elasticity of the high-strength un-bonded tendons with the energy dissipation capacity of the mild-steel reinforcement to control the inelastic response of the structure.

The use of post-tensioning in concrete structures to resist gravity loads is a well established technology with wide application. Recent advances in design practice and analysis techniques are demonstrating that post-tensioning also offers significant cost and performance benefits when incorporated into seismic resisting concrete walls and frames.

Properly proportioned, such a system provides improved ductility and is less prone to physical damage during earthquake shaking. Moreover, the post-tensioning provides a significant strength enhancement, substantially reducing quantities of conventional reinforcement in flexural members,

Figure 1 – Project overview

resulting in more compact dimensions and improved constructability.

Specialized concrete mixes, with high-volume replacement of cement with blast-furnace slag, were also integrated into the design to reduce the quantity of Portland cement: an energy intensive material.

This case-study describes key issues related to the design, analytical modeling, and construction of this novel hybrid system.

Project Description

The project is a combination of four distinct elements: a 4-story office building and conference center, a multi-unit residential building, ground floor retail space, and an underground parking garage. See Figures 1 and 2.

This study focuses on the David Brower Center office structure, which, with its distinctive elongated bullet shape, forms the northern boundary of the complex. Oxford Plaza is a multi-unit residential building situated directly to the south and is supported on a second-story PT podium slab over ground floor retail space. The single level below-grade parking covers the entire site.

The total floor area of the complex is 225,000 sq. ft. With plan dimensions of approximately 62' x 196', the Brower Center comprises roughly 49,500 sq. ft. of space. The total project construction cost was approximately $50M. The Brower Center alone is estimated to cost around $15.3M.

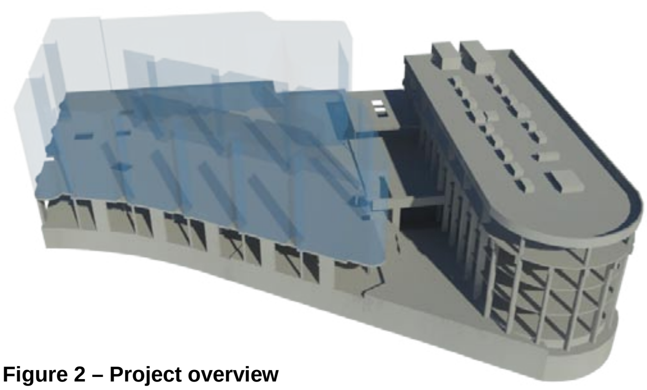

Figure 2 – Project overview

The David Brower Center incorporates a dual seismic force resisting system, with two centrally located C-shaped cores acting in conjunction with two transverse moment frames at the ends of the building as described in Figure 3. The frames are located outboard of the central core walls to control torsional response. In the longitudinal direction the core walls resist the entire seismic load.

The gravity system consists of concrete columns supporting 9 inch PT slabs. Longitudinal bays are spaced at 27 ft. Along the short axis two 16 ft. bays flank a central 28 ft. bay.

The foundation consists of a mat slab between 2' to 2'-6" in thickness. Deep foundations were avoided by resolving lateral system overturning forces into a moment couple between the ground floor slab and the mat slab. Below the ground floor, the walls and frames are designed to remain elastic.

Seismicity and Sustainability

The site is near a major fault system capable of producing a 7.0+ magnitude earthquake. An earthquake of such intensity is predicted to occur, with near certainty, within the next 30 years – well within the expected lifespan of this structure. A typical code-compliant building would be considered well-performing if it remained standing and allowed safe evacuation of the inhabitants after a major seismic event, even if substantial structural damage occurred. It is often the case in such instances that the primary structural system retains sufficient residual strength to remain in service but that residual drift and widespread damage to non-structural components renders it unfit for continued use. Permanent offsets can interfere with the functioning of doors, windows, elevator shafts and other components to such an extent that the structure must be demolished and rebuilt.

Clearly a major aspect of sustainable construction in this setting is continued functionality of the structure after the occurrence of a large earthquake. Protection of the investment in energy and materials is a key "green" construction goal.

Concrete and Carbon Footprint

The major component of embodied energy and related "carbon footprint" for a concrete structure is the cement used in the concrete mix. Cement production is very energy intensive and a significant source of global greenhouse-gas emissions. Aggressive use of blast furnace slag, a waste product of steel production, is estimated to have saved 1,000,000 lbs. of CO_2 emissions.

Typical cement replacement ratios for the project ranged from 50% for slabs, columns and walls to 70% for the mat foundation. The large reduction in cement used was thus key to achieving the project design goals of high material efficiency along with reduced embodied energy and life-cycle costs.

Design Approach

The design of the structure is based on the seismic loads specified in the 2001 edition of the California Building Code, (CBC, 2002) for dual concrete shear wall / moment frame systems.

The unusual geometry and configuration of the building required careful proportioning and relied on capacity design principles to ensure that inelastic mechanisms would form in a predictable and reliable manner. To verify and refine the design of structural system, non-linear time-history simulations were performed to predict the response of the building.

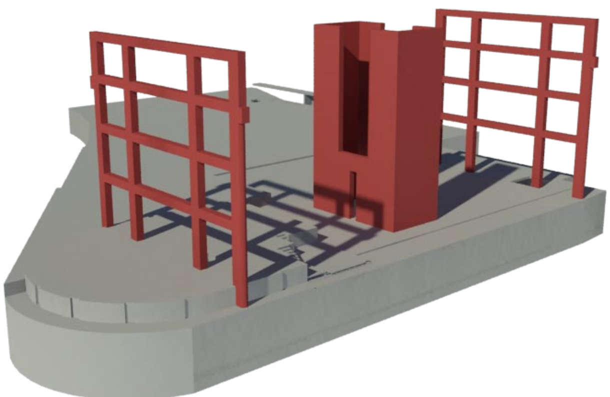

Figure 3 – Structural system

The moment frames and the core walls incorporate post-tensioning and contribute to the re-centering effect.

Response of Post-tensioned Concrete Systems

The use of hybrid post-tensioned concrete for seismic resistance is not unique to this application. Though not widespread in practice, the advantages these systems can provide are increasingly being exploited to improve the seismic performance and efficiency of structures, (Panian, Steyer, Tipping, 2007). The behavior of post-tensioned flexural elements can be conceptualized by considering a simplified cantilever supported by a rotational spring and damper shown in Figure 5.

The response of the cantilever is characterized by the superposition of two fundamental mechanisms of resistance: a non-linear elastic restoring spring representing the effect of the post-tensioning tendons, and a non-linear inelastic yielding component representing the conventional reinforcement. Both the tendons and the reinforcement contribute to the overall flexural strength of the flexural element. The mild steel reinforcement yields to dissipate energy, while the unbounded tendons remain elastic to provide a positive restoring force and center the structure after inelastic response. This idealized flexural force-deformation response of the cantilever as the superposition of its components is described in Figure 4.

The elastic component, Figure 4a, represents the response with the contribution of the post-tensioning only. Figure 4b, represents the contribution of the mild steel reinforced concrete section without the effect of the post-tensioning. As seen in Figure 4c the hysteresis loop of a hybrid wall containing mild steel and post-tensioning exhibits a flag-shaped loop that results from the superposition of two component curves.

The elastic restoring component is proportioned to be somewhat larger than the yielding component, which means that slightly more than half the total resistance is derived from the post-tensioning. This ensures a favorable “rocking” response and a consistent tendency to re-center following an earthquake.

Plastic Hinge Mechanics

As in typical concrete flexural analysis, cross-sections are assumed to remain plane throughout inelastic response. Inelastic rotations of the hinge are estimated as the product of the plastic hinge length and the curvature. Establishing equilibrium forces for a concrete flexural element with un-bonded post-tensioning takes a similar approach. However, estimating the strain of the tendons requires consideration of

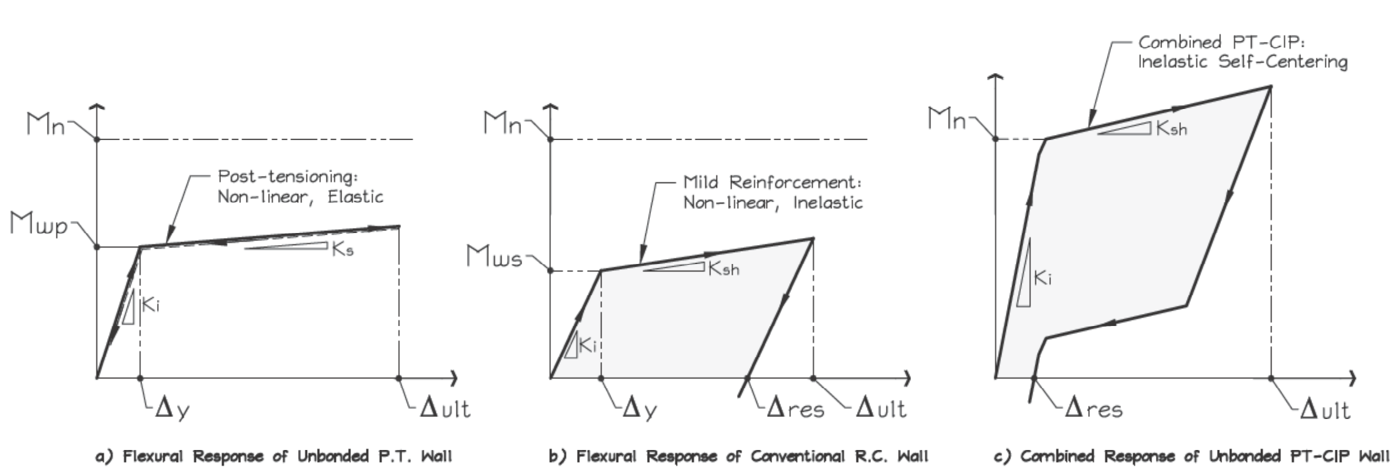

Figure 4 – Hysteretic response of hybrid PT element

the kinematics of the entire member, because stress changes in the tendons result only from the movement of the end anchors. Strains in the un-bonded strands are distributed over the entire tendon length, not just the length of the plastic hinge.

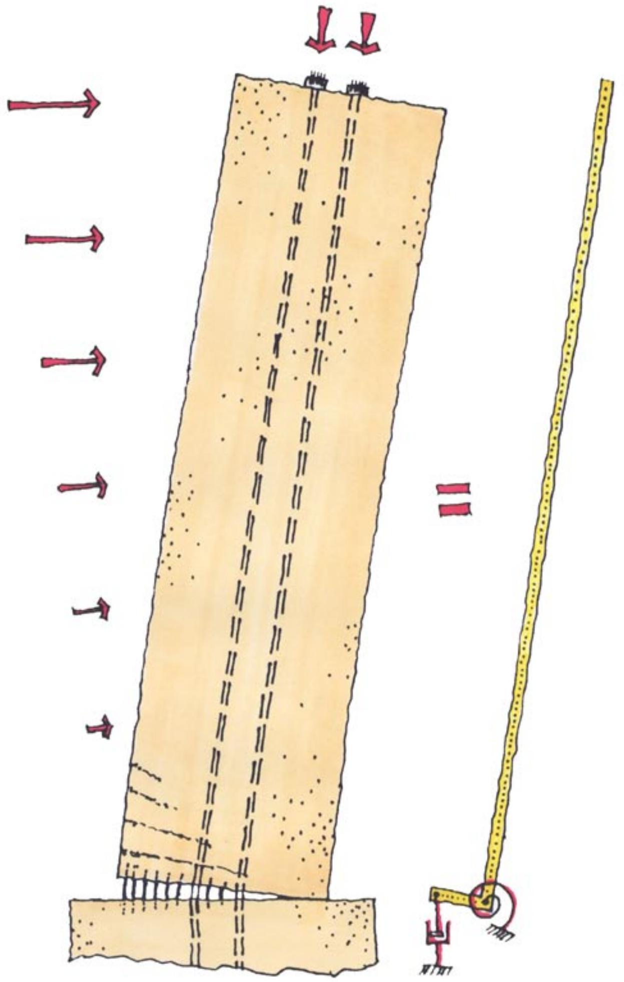

Figure 5 – Mechanism study

This means that as the cross-section reinforcement yields, the tendons remain elastic, and are thus protected from premature yielding.

If the moment provided by these tendons remains greater than the plastic moment of the yielded reinforcement, the tendons can close the plastic hinge, causing little or no residual deformations.

Proportioning Reinforcement and PT

Proportioning the hybrid flexural elements requires that specific attention be paid to the strains in the tendons and concrete to ensure a stable failure mechanism. To promote the desired mechanism and maximize system ductility, it is critical to avoid the premature fracture of tendons and crushing of concrete.

Key aspects of proportioning the flexural elements are as follows (Panian, Steyer, Tipping, 2007):

- Adequate strength to meet code requirements,
- The proportion of flexural strength from PT vs. total flexural strength roughly greater than 0.55, and
- Enough concrete area and strength to keep the compression toes well-intact at maximum expected curvature.

Recognizing and exploiting the overall symmetry of opposing non-coupled C-shaped walls allowed a configuration of tendons and reinforcing that would not have been otherwise possible with an isolated asymmetric structure. The tendons are placed in the flanges and mild-steel reinforcement is concentrated at the flange tips to reduce compressive strains on the concrete and tensile strains in the strands. This allowed the optimization of the wall sections and enhanced the ductility of the structure.

Nonlinear Response-History Analysis

To test the design under simulated earthquake shaking, a non-linear time-response analysis (NLRHA) was performed using spectrally-matched site-specific ground motion predictions. The analysis was conducted using CSI Perform-3D. The inelastic flexural behavior of the post-tensioned walls and frames was modeled with inelastic fiber element sections.

The elements in the model were made of materials with the capability to yield and generate hysteretic behavior to estimate the expected behavior of the concrete, rebar and PT components. The behavior of the un-bonded tendons is achieved by connecting them only to the wall elements at the top and bottom of the wall; these correspond to the locations actual anchorage zones. The rebar and concrete elements, by contrast, are connected at each floor level, which is analogous to the real bonding and plastic hinge behavior.

The practical value of the NLRHA was evident both as a design tool and as a verification tool. Preliminary models allowed the design to be fine tuned, while the final analyses provided confirmation that the design satisfied the performance objectives.

The results of the NLRHA were used in conjunction with capacity design principles (Priestley, Paulay, 1992 & Priestley, Calvi, Kowalsky, 2007) to predict forces in "protected" elements, eliminate non-ductile failure modes, and ensure a stable flexural mechanism.

Maximum inter-story drifts are predicted to be 1.5% and 2.5% for the Design Basis Earthquake (DBE) and the

Maximum Capable Earthquake (MCE) respectively. Residual drifts in each case were negligible.

The peak average strain in the PT tendons was significantly less than the offset yield strain of 0.008 for the DBE earthquake. For the MCE earthquake, the strains were slightly above the yield point at the extreme wall tendons. The reinforcement is expected to experience significant yielding under both MCE and DBE motions, but fracture is not anticipated for either hazard level. Maximum concrete strains are predicted to remain less than 0.008, below the ultimate confined concrete strain capacity of 0.010.

Construction Detailing

A critical aspect of seismic detailing for structural concrete is confinement. Section ductility and good hysteretic behavior require that core concrete retain its integrity under high compressive strains and repeated load reversals. This becomes even more critical in post-tensioned seismic resisting systems, where the added imposed compressive forces push concrete close to its ultimate crushing strain. Careful detailing of lateral reinforcement is required to ensure that ductile steel yielding rather than brittle concrete crushing is the controlling failure mode. Figure 6 describes the core wall reinforcing details at the plastic hinge location.

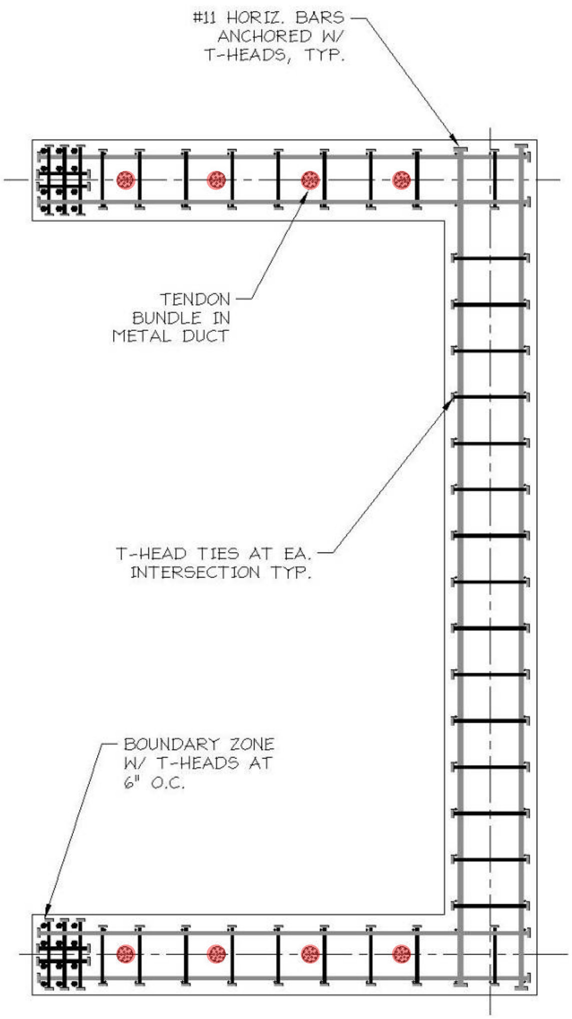

Figure 6 – PT core wall section

Figure 7 – PT core wall construction showing anchor block-out

Given the size of vertical flexural bars in the core walls (#14 at base, #11 at hinge region) and the architectural desire to minimize overall core dimensions, traditional hooked cross-ties were not practical in the first two stories of the cores. Headed bars were used at the most congested sections. Their compact shape allows them to be closely spaced while easily engaging the intersections of horizontal and vertical bars.

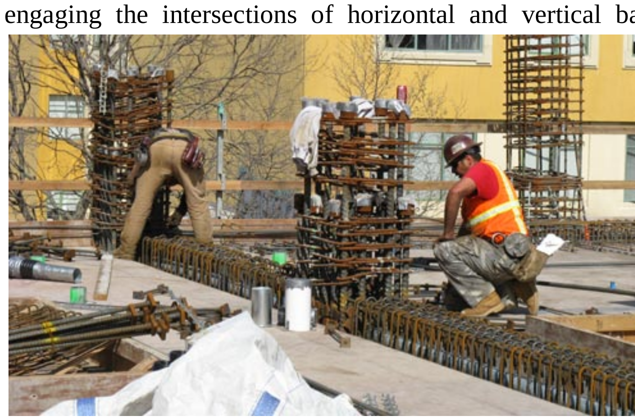

Figure 8 – PT moment-frame construction

These were provided at 6” o.c. in the boundary zones and typically 12” o.c. each way in the wall webs. See Figure 7.

The required vertical and horizontal reinforcing is curtailed above the plastic hinge region, allowing confinement above the third floor to be traditional hooked cross-ties. Splicing of flexural reinforcement at and below the hinge zone was achieved using Type II mechanical couplers. As these couplers become large for #11 and #14 bars, it is important to define their location and required stagger to avoid excessive congestion. Even so, careful concrete placement and consolidation is required at the densest locations.

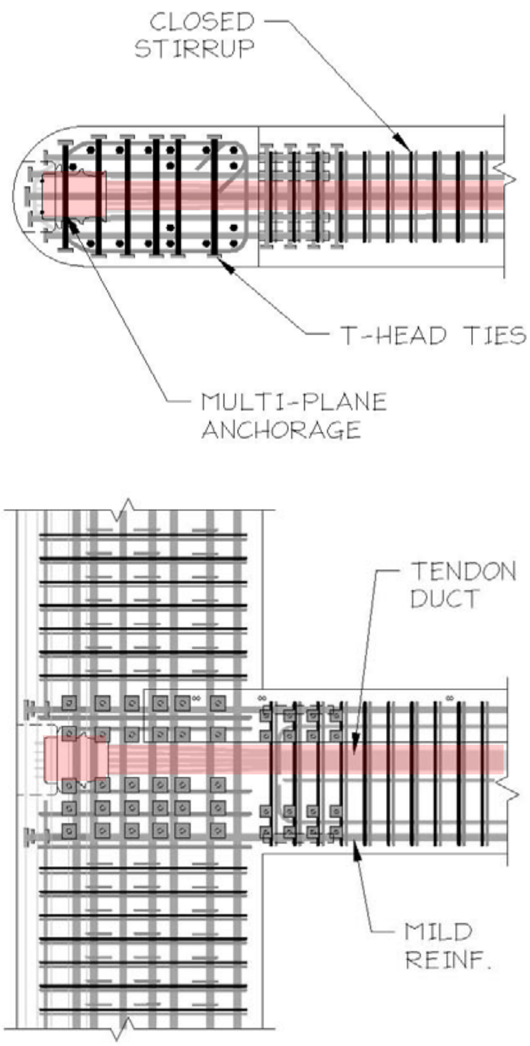

Figure 9 – PT moment-frame joint details

Detailing of the PT moment frames presented similar challenges. The building geometry established a 3-bay layout with a 28 ft. center bay flanked by two 16.5 ft. end bays. The relative shortness of the end bays required significant rotational ductility and a high level of confinement. With a typical beam dimension of 28 in (D) x 24 in (W), accommodation of PT ducts, wedge plates, longitudinal and transverse reinforcing requires careful layout. Figure 8 shows one of the frames under construction.

Detailed drawings of beam sections and elevations showing each component drawn to scale were critical in determining proper fit. See Figure 9.

The post-tensioning tendons consist of bundles of 0.6” diameter, individually sheathed and greased tendons in corrugated metal ducts. This approach allows the ducts to be cast in place and the tendons to be installed after all of the concrete is placed. Bundles range in size from 11 to 17 strands that terminate in multi-strand anchorages.

Figure 10 – Detail at moment frame PT anchor

Concrete confinement in the anchorage region begins with a #5 spiral which is integral to the multi-strand casting. Additional horizontal bars and cross ties in the anchorage zone help to distribute the concentrated tendon reactions across the full core section. Design of these added bars is based on strut and tie modeling of the tendon forces.

Tendon stressing of the moment frames was straight forward. A single multi-strand hydraulic jack was suspended by crane at the exterior column face and the strands were stressed together in one operation.

Figure 11 – Stressing jack for wall tendons

The stressing operation for the vertical tendons in the core walls was similar, but required a block-out at the base of the walls to allow installation of the tendons. The bottom block-outs are located in the basement level, which is designed to remain elastic. Mechanical couplers are used to splice horizontal and vertical bars within the block-out. The block-outs are poured solid to complete the walls after the tendons are stressed.

As the anchorages on top of the core and at the moment frames are located in exterior members, corrosion protection is a concern. Exterior weather caps over solid grouted anchor pockets are the first line of defense. The tendon sheaths are sealed to the cast fittings and internal ports allow grease to be injected into the completed assembly to provide maximum protection.

Summary

Several benefits can be realized by the introduction of post-tensioned reinforcement to concrete seismic lateral resisting

Figure 12 – Exterior of PT moment frame

systems. Direct structural benefits include improved ductility, reduced mild steel reinforcing and self-centering behavior. The ability to eliminate residual drift represents a major innovation in seismic design.

Additionally, savings in carbon footprint and greenhouse gas emission were realized through integrating high-slag concrete in the structural system. These characteristics played an important role in meeting the sustainability goals of the David Brower Center.

Acknowledgments

Architect:	Solomon ETC
Owner/Developer:	Equity Community Builders / RCD
Contractor:	Cahill

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